Example 4c: General Loading Option for RUC analysis

This example demonstrates how to apply a general mechanical loading history to a given repeating unit cell. This option, specified by LOP=99, allows the user to specify all six mechanical loading components applied to the composite. Of course, for each component only a single stress or strain may be specified, not both. This example simulates a complex thermomechanical loading history on a continuous fiber SiC/Ti-21S composite that involves application of stresses and strains in the x_1-x_2 plane. This loading profile might mimic a material point on the skin of an aerospace vehicle or engine housing. The 26×26 circular fiber approximation RUC architecture is employed. For more information on the code's general mechanical loading option, see the MAC/GMC 4.0 Keywords Manual Section 4.

MAC/GMC Input File: **example_4c.mac**

```
MAC/GMC 4.0 Example 4c - RUC analysis general loading option
*CONSTITUENTS
  NMATS=2
  M=1 CMOD=6 MATID=E
  M=2 CMOD=4 MATID=A
*RUC
  MOD=2 ARCHID=13 VF=0.25 R=1. F=1 M=2
*MECH
  LOP=99
  NPT=6 TI=0.,300.,310.,2310.,2320.,2620. MAG=0.,0.,0.01,0.01,0.,0. &
    MODE=1,1,1,2,2
  NPT=6 TI=0.,300.,310.,2310.,2320.,2620. MAG=0.,0.,0.005,0.005,0.,0. &
    MODE=1,1,1,2,2
  NPT=2 TI=0.,2620. MAG=0.,0. MODE=2
  NPT=2 TI=0.,2620. MAG=0.,0. MODE=2
  NPT=2 TI=0.,2620. MAG=0.,0. MODE=2
  NPT=6 TI=0.,300.,310.,2310.,2320.,2620. MAG=0.,0.,0.0075,0.0075,0.,0. &
    MODE=1,1,1,2,2
*THERM
  NPT=6 TI=0.,300.,310.,2310.,2320.,2620. TEMP=23.,650.,650.,650.,650.,23.
*SOLVER
  METHOD=1 NPT=6 TI=0.,300.,310.,2310.,2320.,2620. STP=1.,0.2,2.,1.,1.
*PRINT
  NPL=6
*XYPLOT
  FREQ=1
  MACRO=4
   NAME=example_4c X=1 Y=7
   NAME=example_4c X=2 Y=8
   NAME=example_4c X=6 Y=12
   NAME=example_4c X=100 Y=101
  MICRO=0
*END
```

Annotated Input Data

1) Flags: None

2) Constituent materials (***CONSTITUENTS**) [KM_2]:
   Number of materials: 2   (NMATS=2)
   Materials: SiC fiber   (MATID=E)
                             Ti-21S   (MATID=A)
   Constitutive models: SiC fiber: linearly elastic   (CMOD=6)
                             Ti-21S matrix: Isotropic GVIPS (CMOD=4)

3) Analysis type (***RUC**) → Repeating Unit Cell Analysis [KM_3]:
   Analysis model: Doubly periodic GMC   (MOD=2)
   RUC architecture: 26×26 circular fiber, rect. pack (ARCHID=13)
   Fiber volume fraction: 0.25   (VF=0.25)
   RUC aspect ratio: 1. (square pack)   (R=1.)
   Material assignment: SiC fiber   (F=1)
                             Ti-21S matrix   (M=2)

4) Loading:
 a) Mechanical (***MECH**) [KM_4]:
   Loading option: general loading   (LOP=99)

   Component #1 (ε_{11} or σ_{11})
   Number of points: 6   (NPT=6)

Times (TI=) (sec.)	0.		300.		310.		2310.		2320.		2620.
Magnitudes (MAG=)	0.		0		0.01		0.01		0.		0.
Control (MODE=)		strain		strain		strain		stress		stress	

   Component #2 (ε_{22} or σ_{22})
   Number of points: 6   (NPT=6)

Times (TI=) (sec.)	0.		300.		310.		2310.		2320.		2620.
Magnitudes (MAG=)	0.		0		0.005		0.005		0.		0.
Control (MODE=)		strain		strain		strain		stress		stress	

   Component #3 (ε_{33} or σ_{33})
   Number of points: 2   (NPT=2)

Times (TI=) (sec.)	0.	2620.
Magnitudes (MAG=)	0.	0.
Control (MODE=)		stress

   Component #4 (γ_{23} or σ_{23})
   Number of points: 2   (NPT=2)

Times (TI=) (sec.)	0.	2620.
Magnitudes (MAG=)	0.	0.
Control (MODE=)		stress

Component #5 (γ_{13} or σ_{13})
Number of points: 2   (NPT=2)

Times (TI=) (sec.)	0.	2620.
Magnitudes (MAG=)	0.	0.
Control (MODE=)	stress	

Component #6 (γ_{12} or σ_{12})
Number of points: 6   (NPT=6)

Times (TI=) (sec.)	0.	300.	310.	2310.	2320.	2620.
Magnitudes (MAG=)	0.	0	0.0075	0.0075	0.	0.
Control (MODE=)		strain	strain	strain	stress	stress

The simulated loading constitutes a state of plane stress in the x_1-x_2 plane, thus the stress associated with components 3 – 5 are kept at zero. The first loading segment involves the in-plane strain components being constrained (i.e., kept at zero) during which time a heat-up is specified in the thermal loading. Then, in-plane normal and shear strains are quickly applied and then held for 2000 sec. The control mode next switches from strain to stress for all three in-plane components, and the mechanical loading is reduced to zero in stress control. Finally, the composite is kept globally stress-free as the temperature is reduced during the final segment. This simulates a (fictitious) mission profile that might be encountered at a material point on the skin of an aerospace vehicle or engine as the vehicle warms up, takes off, flies, lands, and cools.

b) Thermal (***THERM**) [KM_4]:
Number of points: 6   (NPT=6)
Time points: 0., 300., 310., 2310., 2320., 2620. sec.
                  (TI=0.,300.,310.,2310.,2320.,2620.)

Temperature points: 23., 650., 650., 650., 650., 23. °C
                  (TEMP=23.,650.,650.,650.,650.,23.)

c) Time integration (***SOLVER**) [KM_4]:
Time integration method: Forward Euler   (METHOD=1)
Number of points: 6   (NPT=6)
Time points: 0., 300., 310., 2310., 2320., 2620. sec.
                  (TI=0.,300.,310.,2310.,2320.,2620.)

Time step sizes: 1., 0.2, 2., 1., 1. sec.   (STP=1.,0.2,2.,1.,1.)

5) Damage and Failure: None

6) Output:
a) Output file print level (***PRINT**) [KM_4]:
Print level: 6   (NPL=6)

b) x-y plots (***XYPLOT**) [KM_4]:
Frequency: 5   (FREQ=5)
Number of macro plots: 6   (MACRO=6)

Macro plot names:	example_4c	(NAME=example_4c)
Macro plot x-y quantities:	ε_{11}, σ_{11}	(X=1 Y=7)
	ε_{22}, σ_{22}	(X=2 Y=8)
	γ_{12}, σ_{12}	(X=6 Y=12)
	temperature, time	(X=100 Y=101)
Number of micro plots:	0	(MICRO=0)

7) End of file keyword: (***END**)

Results

Figure 4.5 and Figure 4.6 show that during the first loading segment (0 – 300 sec.), while the temperature is increasing from 23 – 650 °C, no strain results and the normal stress components (σ_{11} and σ_{22}) become compressive. This is due to the fact that the composite has been constrained against its natural thermal expansion during this heat-up. The shear stress component remains at zero because the composite does not experience shear thermal expansion (i.e., it is orthotropic). From 300 – 310 sec., the three strain components are quickly applied, and the stress components rise rapidly in response. Next, these three strain components are held constant for 2000 sec., during which time the stress components are free to relax. From 2310 – 2320 sec., the mechanical load, which was applied in strain control, is unloaded under stress control to zero for all three stress components. Finally, the temperature is decreased from 650 – 23 °C from 2320 – 2620 sec., during which time the stress components on the composite are held at zero. Therefore, the normal strain components decrease as the composite contracts while the shear strain remains constant. From Figure 4.6, it is clear that the composite experience permanent normal and shear strains at the completion of this thermomechanical loading history.
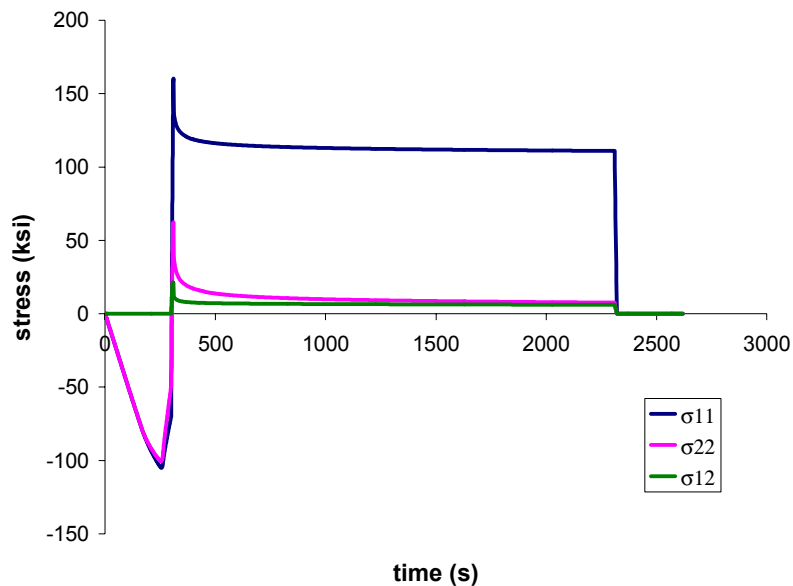

Figure 4.5   Example 4c: plot of the simulated stress vs. time history for a 0.25 fiber volume fraction SiC/Ti-21S composite.
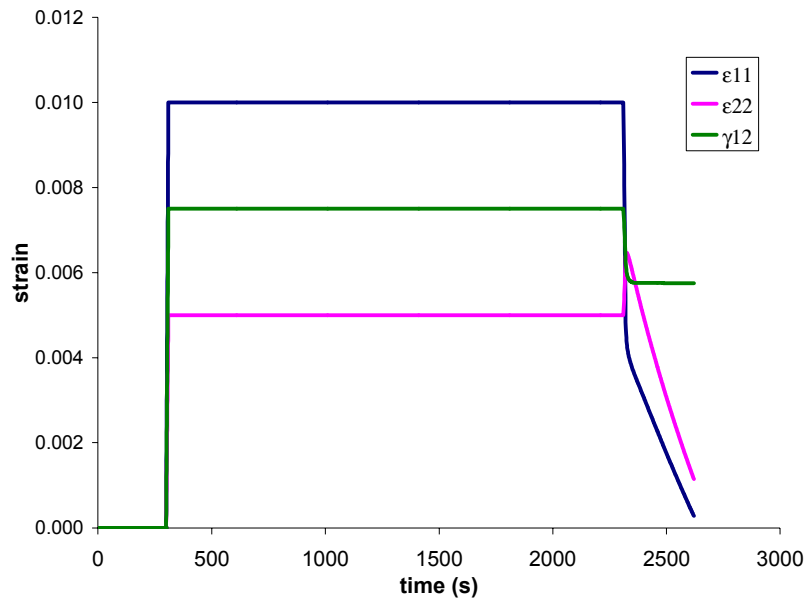
Figure 4.6   Example 4c: plot of the simulated strain vs. time history for a 0.25 fiber volume fraction SiC/Ti-21S composite.